

**HAMPTON UNIVERSITY**  
**NASA FAR Award**  
**FINAL REPORT**  
**SUMMARY OF RESEARCH**

**ADVANCED METHODS FOR AIRCRAFT ENGINE THRUST  
AND NOISE BENEFITS: Nozzle-Inlet Flow Analysis**


**NASA Grant, NAG-1-2249**

**3Year Granted Period**

**Effective Date: 01/01/99**

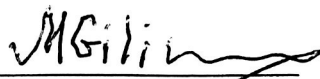
**Expiration Date: 12/31/01**

**Extension Date : 12/31/02**



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**1) Provide a description of the program.**

In this project on the first stage (2000-01), we continued to develop the previous joint research between the Fluid Mechanics and Acoustics Laboratory (FM&AL) at Hampton University (HU) and the Jet Noise Team (JNT) at the NASA Langley Research Center (NASA LaRC). At the second stage (2001-03), FM&AL team concentrated its efforts on solving of problems of interest to Glenn Research Center (NASA GRC), especially in the field of propulsion system enhancement. The NASA GRC R&D Directorate and LaRC Hyper-X Program specialists in a hypersonic technology jointly with the FM&AL staff conducted research on a wide region of problems in the propulsion field as well as in experimental testing and theoretical and numerical simulation analyses for advanced aircraft and rocket engines. The last year the Hampton University School of Engineering & Technology was awarded the NASA grant, [1], for creation of the Aeropropulsion Center, and the FM&AL is a key team of the project fulfillment responsible for research in Aeropropulsion and Acoustics (Pillar I). This work is supported by joint research between the NASA GRC/ FM&AL and the Institute of Mechanics at Moscow State University (IM/MSU) in Russia under a CRDF grant. The main areas of current scientific interest of the FM&AL include an investigation of the proposed and patented advanced methods for aircraft engine thrust and noise benefits. This is the main subject of our other projects, of which one is presented. The last year we concentrated our efforts to analyze three main problems: (a) new effective methods fuel injection into the flow stream in air-breathing engines; (b) new re-circulation method for mixing, heat transfer and combustion enhancement in propulsion systems and domestic industry application; (c) convexity flow. The research is focused on a wide regime of problems in the propulsion field as well as in experimental testing and theoretical and numerical simulation analyses for advanced aircraft and rocket engines (see, for example, Figures 4). The FM&AL Team uses analytical methods, numerical simulations and experimental tests at the Hampton University campus, NASA and IM/MSU.

The goals of the FM&AL programs are twofold: **1)** to improve the working efficiency of the FM&AL team in generating new innovative ideas and in conducting research in the field of fluid dynamics and acoustics, basically for improvement of supersonic and subsonic aircraft engines, and **2)** to attract promising minority students to this research and training and, in cooperation with other HU departments, to teach them basic knowledge in Aerodynamics, Gas Dynamics, and Theoretical and Experimental Methods in Aeroacoustics and Computational Fluid Dynamics (CFD). The research at the HU FM&AL supports reduction schemes associated with the emission of engine pollutants for commercial aircraft and concepts for reduction of observables for military aircraft. These research endeavors relate to the goals of the NASA Strategic Enterprise in Aeronautics concerning the development of environmentally acceptable aircraft. It is in this precise area, where the US aircraft industry, academia, and Government are in great need of trained professionals and which is a high priority goal of the Minority University Research and Education (MUREP) Program, that the HU FM&AL can make its most important contribution.

In general, the Fluid Mechanics and Acoustics Laboratory at Hampton University (FM&AL) jointly with the NASA Glenn Research Center was conducted four connected sub-projects under

the reporting project. Basically, the FM&AL Team has been involved in joint research with the purpose of theoretical explanation of experimental facts and creation of the accurate numerical simulation technique and prediction theory for the solution current problems in propulsion systems of interest to the NASA and NAVY agencies. This work is also supported by joint research between the NASA GRC and the Institute of Mechanics at Moscow State University (IM/MSU) in Russia under the CRDF grant, # RE1-2068. The research is focused on a wide regime of problems in the propulsion field as well as in experimental testing and theoretical and numerical simulation analyses for advanced aircraft and rocket engines. The FM&AL Team uses analytical methods, numerical simulations and possible experimental tests at the Hampton University campus. The fundamental idea uniting these sub-projects is to use untraditional 3D corrugated and composite nozzle and inlet designs and additional methods for exhaust jet noise reduction without essential thrust lost and even with thrust augmentation.

These sub-projects are:

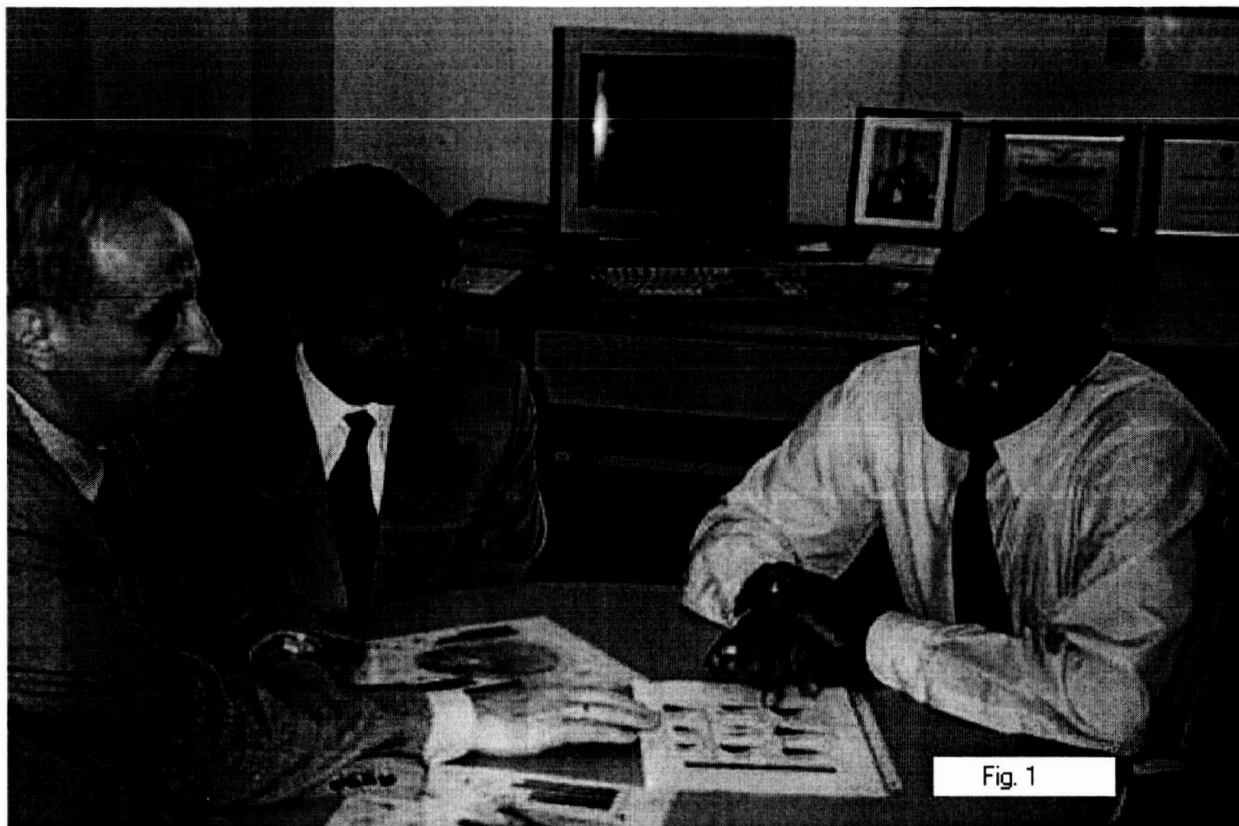
- A)** Performance and acoustics of a Bluebell-shaped and Telescope-shaped designs.
- B)** An analysis of sharp-edged nozzle exit designs for effective fuel injection into the flow stream in air-breathing engines: triangular-round, diamond-round and others nozzles.
- C)** Measurement technique improvement for the HU Low Speed Wind Tunnel; the new course in the field of aerodynamics, teaching and training of HU students; experimental tests of Möbius-shaped screws: research and training.
- D)** Supersonic inlet shape optimization.

The main outcomes during reporting period are:

- 1) Publications: Three AIAA papers has been presented at conferences: **1.1** The AIAA Paper #00-3170, 36th AIAA/ASME/SAE/ASEE Joint Propulsion Conference, 17-19 June, 2000, Huntsville, AL; **1.2** The AIAA Paper #01-1893, AIAA/NAL-NASDA-ISAS 10<sup>th</sup> International Space Planes and Hypersonic Systems and Technologies Conference, 24-27 April, 2001, Kyoto, Japan; **1.3** The AIAA Paper #01-3204, 37th AIAA/ASME/SAE/ASEE Joint Propulsion Conference, 08-11 July/Salt Lake City, UT.
- 2) Grants and proposals: The HU/FM&AL was awarded the NASA grant NAG-3-2495 on October, 2000 and the laboratory is a primary US research team in the joint project under the CRDF award granted to the NASA GRC and IM/MSU (Russia) on July, 2000.
- 3) Theory and numerical simulations: Analytical theory, numerical simulation, comparison of theoretical with experimental results, and modification of theoretical approaches, models, grids etc. have been conducted for several complicated 2D and 3D nozzle and inlet designs using NASA, ICASE and IM/MSU codes based on full Euler and Navier-Stokes solvers: CFL3D, FLUENT, and GODUNOV, and others.
- 4) Experimental Tests: **4.1** New course: "Advanced Aerodynamics and Aircraft Performance" lectured on spring semester, 2001; training and experimental test research using the HU LSWT. **4.2** Small scale Möbius-shaped screws were tested in different conditions and their application has shown essential benefits by comparison with traditional designs.
- 5) Installation in the FM&AL computer system: second software TECPLOT 8.0 for the UNIX SGI workstation and free TECPLOT 7.5 for the PC Dell computer, and 2D and 3D GRIDGEN (version 9) for the UNIX SGI as well as installation of two free NASA codes 3D MAG and VULCAN.
- 6) Students' Research Activity: Involvement of four undergraduate and three graduate students as research assistants in the current research project.

Below, several illustrations of our research, training and teaching activities under reporting project as well as some achievements will be presented with short descriptions of these illustrations.

**Figure 1.** The leading personnel is shown during the current report preparation in the FM&AL Headquarters Office located at the Hampton University campus, Olin Bldg., room 503.



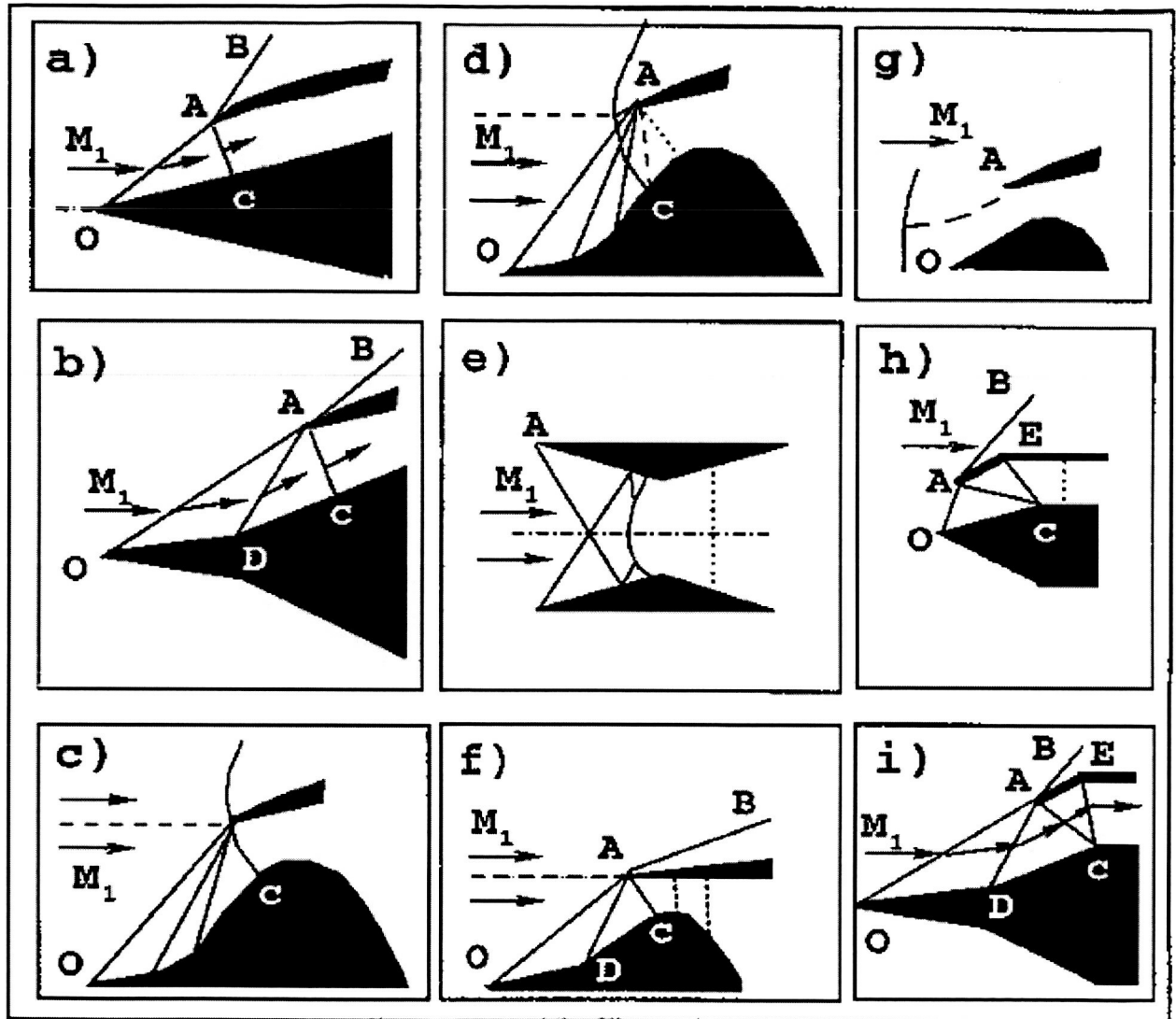
**Fig.1 Hampton University Fluid Mechanics and Acoustics Laboratory (FM&AL) leading personnel in the FM&AL Headquarters Office. From the right to the left are: Principal Investigator Dr. Morris H. Morgan, Dean of the School of Engineering and Technology; Graduate Student, Research Assistant Mr. Kaushal Patel and Primary Investigator, Research Professor Dr. Mikhail Gilinsky.**

## **Figure 2. INLET NUMERICAL SIMULATIONS**

The main purpose of a supersonic inlet is to slow down the gas flow from supersonic speed to low subsonic speed before the chamber (compressor). Simultaneously, the total pressure should have minimal loss for effective combustion in the chamber. The first investigations and analysis of this problem took place in the 60's. For 2D and axisymmetric inlets, the investigations showed that flow total pressure loss through a set of inclined oblique shock waves with a last normal shock wave is essentially less than through a unique detached shock wave before the inlet. Several inlet flow regimes are possible for supersonic inlets. These regimes schematically are shown in Figures 2a-i.



# SUPERSONIC INLET SCHEMES



**Fig.2 Supersonic inlet schemes:** a) two shock waves at the inlet and one external at the cowl; b) three plus one; c) three with a detached shock wave at the cowl; or d) continuous compressive waves along a curved inlet surface (forebody) with detached shock wave at the cowl; e) internal compression through shock waves system; f) partial external and internal compression; g) detached shock wave before the inlet; h) inlet with moving cowl door and three shock waves; i) inlet with moving cowl door and four shock waves.

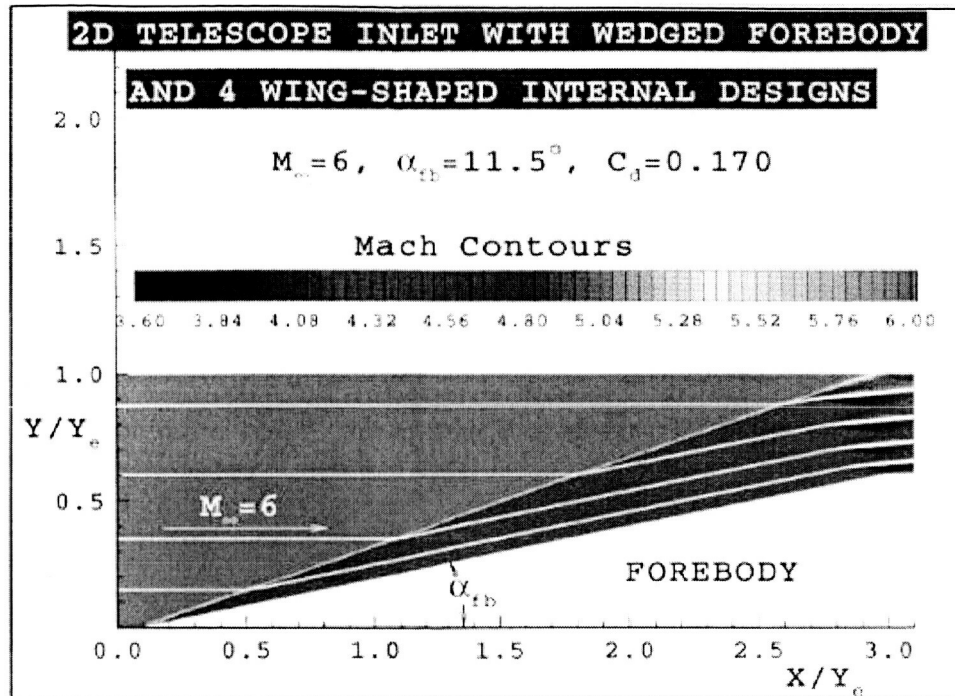


Fig.3 2D Telescope-shaped inlet with 4 internal designs; Mach contours.

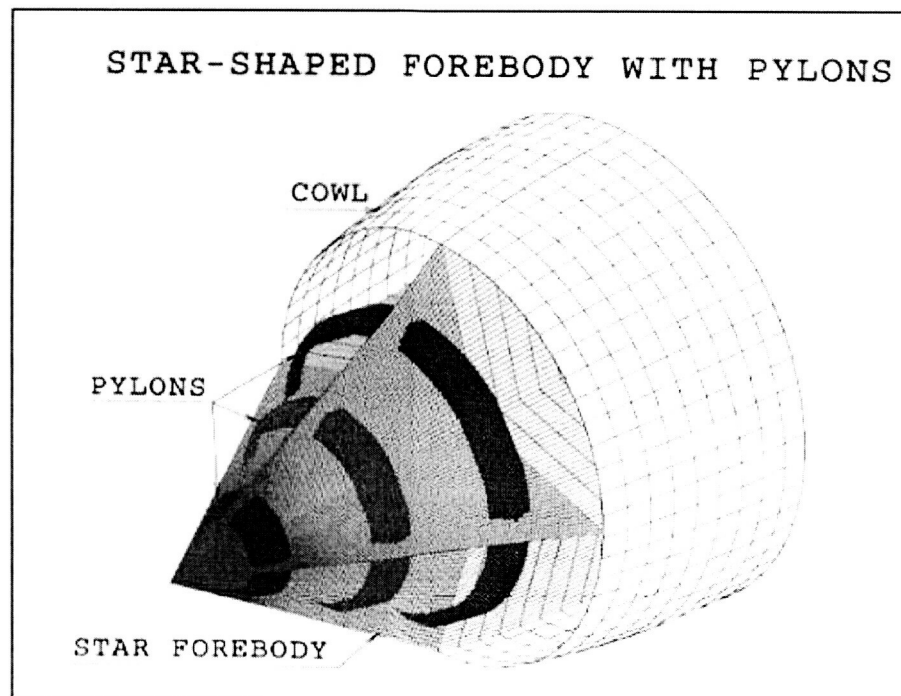


Fig.4 Star-Telescope-shaped inlet with 3 pylons for efficient fuel mixing.

### Figures 3 and 4. Telescope Inlet Application.

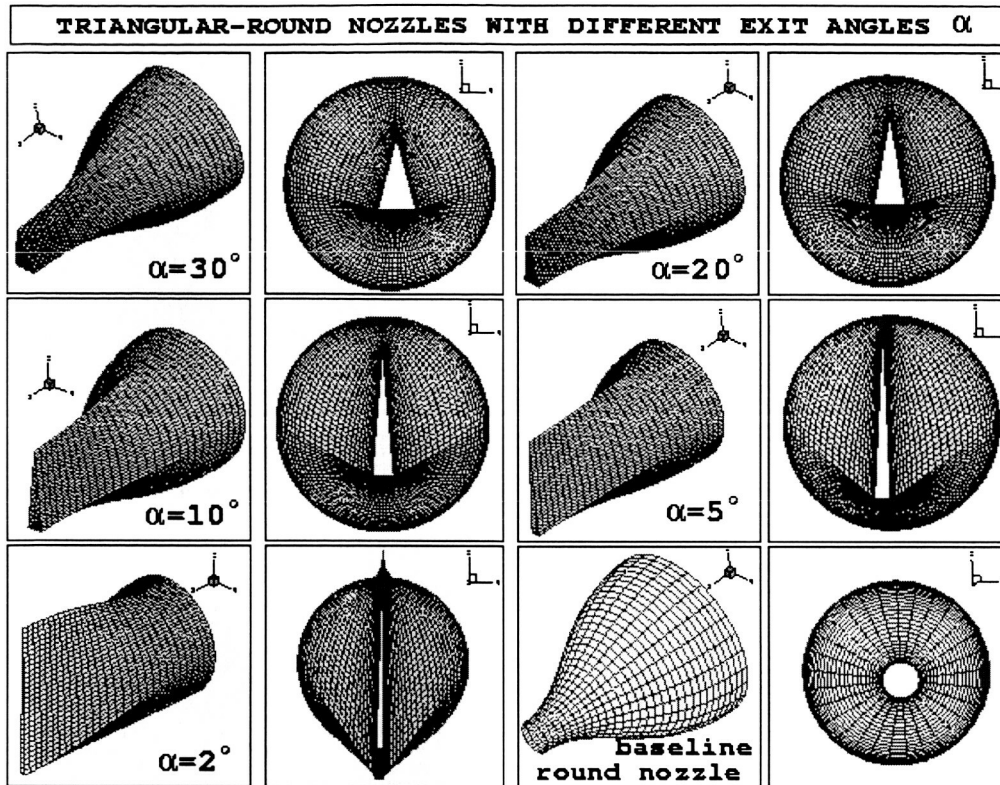
During several years, FM&AL researcher developed proposed and already patented untraditional nozzle designs such as Bluebell and Telescope nozzles. Most of these designs can be employed

for a supersonic inlet improvement. In particular, the Telescope nozzle and all results of theoretical analysis of this concept are useful. In this case, the energy of the turned flow along the forebody wall can be used for creation of additional thrust. The mutual locations, sizes and angles of the internal plates (thin airfoils) are very important for efficiency of the application. Optimal values of geometric parameters were determined from multi-parametric numerical simulations based on the modified marching Krayko-Godunov code. The effect of four thin airfoils installed at the minimal cross section (near the corner point) is illustrated in Figure 3. Here Mach contours and corresponding streamlines are shown for the 2D Telescope inlet with a wedged forebody. This design provides a forebody drag reduction of 25%. Obviously, the same approach is applicable for other designs, such as transition sections inside variable cross section supersonic tunnels, blunt bodies with several ring-shaped sheets, etc. The star-shaped forebody with 3 ring-shaped pylons is shown in Figure 4. The pylon cross section is a thin airfoil. Its chord inclination is directed so that it produces thrust augmentation. These pylons are located in different streamlines of the compressible flow behind the bow shock wave. Therefore, the fuel injected downstream will mix with air stream uniformly creating premixed flow.

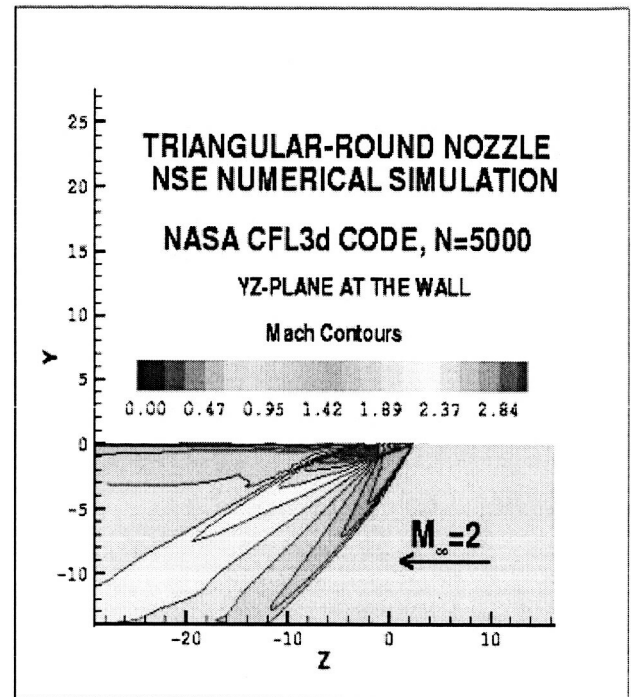
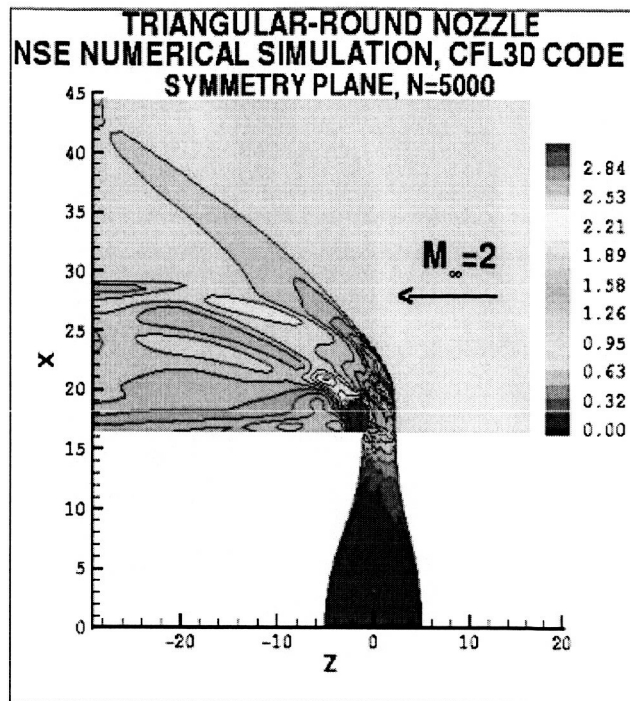
### **Figures 5 and 6. Triangular-Round Nozzles.**

A new convergent and convergent-divergent triangular-round nozzle (T-R nozzle) was designed in accordance with the request of the NASA LaRC Hyper-X Program management. Experimental tests of such design will be conducted at the NASA LaRC and NASA Marshall Flight Center. Several modifications of the design were proposed and drafted by the FM&AL Team. In the first set of T-R designs, smooth curves for the nozzle wall internal contour along the nozzle axis were used. These curves were composed by two coupled parabolas which join two corresponding points: at the initial circle of the round cross section of the nozzle inlet (A) with the ending triangular cross section of the nozzle exit (B). Based on such approach, several T-R nozzle designs were constructed, and the examples of such designs are shown in Figure 5. Here different designs correspond to different angle,  $\alpha$ , at the triangle top of the triangular nozzle exit. All shown designs have the same exit area what equal the circle area of the traditional baseline sonic divergent nozzle. Everybody, experienced in numerical simulation methods and its application in aerodynamics and acoustics, can understand possible difficulties what appear for such design flow numerical simulation. For the computational domain vicinity of sharp tops, a programmer must use special grids or analytical approximation for a satisfactory resolution of numerical solution of the. Nevertheless some preliminary results were obtained using NASA CFL3d code. Such example is shown in Figure 6. In the left portion of this figure, Mach contours are shown for plane of symmetry for the T-R nozzle flow for the triangular nozzle exit angle,  $\alpha=30^\circ$ , and for exhausted jet to the supersonic cross flow with Mach Number,  $M=2$ . In the right portion, Mach contours are shown for the flow at the lower wall of the duct. One can see that in this case an oblique shock wave forms at the exhausted jet and any separation zone at the front of it doesn't occur. For comparison, traditional round nozzle exit application leads to the formation such separate zone and a drag of exhausted jet in the last case essentially bigger, especially, in vicinity of nozzle exit. This result gives a hope of possible efficiency of the T-R nozzle design application for mixing and higher penetration of injecting (fuel) jet to the high speed cross air flow into combustor duct. For the case shown in Figure 6, Reynolds number is equal,  $Re=10^5$ , and the benefit for jet penetration to the duct flow is  $\sim 20\%$  with more efficient mixing downstream. Several other T-R convergent-divergent

nozzle designs were constructed and tested numerically. At the present time, an analysis of all such designs is conducting using more powerful supercomputers and effective NASA and IM/MSU codes for numerical simulation of non-equilibrium flows of hydrogen-air mixtures.



**Fig.5 Triangular-Round Nozzles based on the convergent sound baseline nozzle with the same inlet and exit areas and with different angles  $\alpha$  at the exit triangular top.**

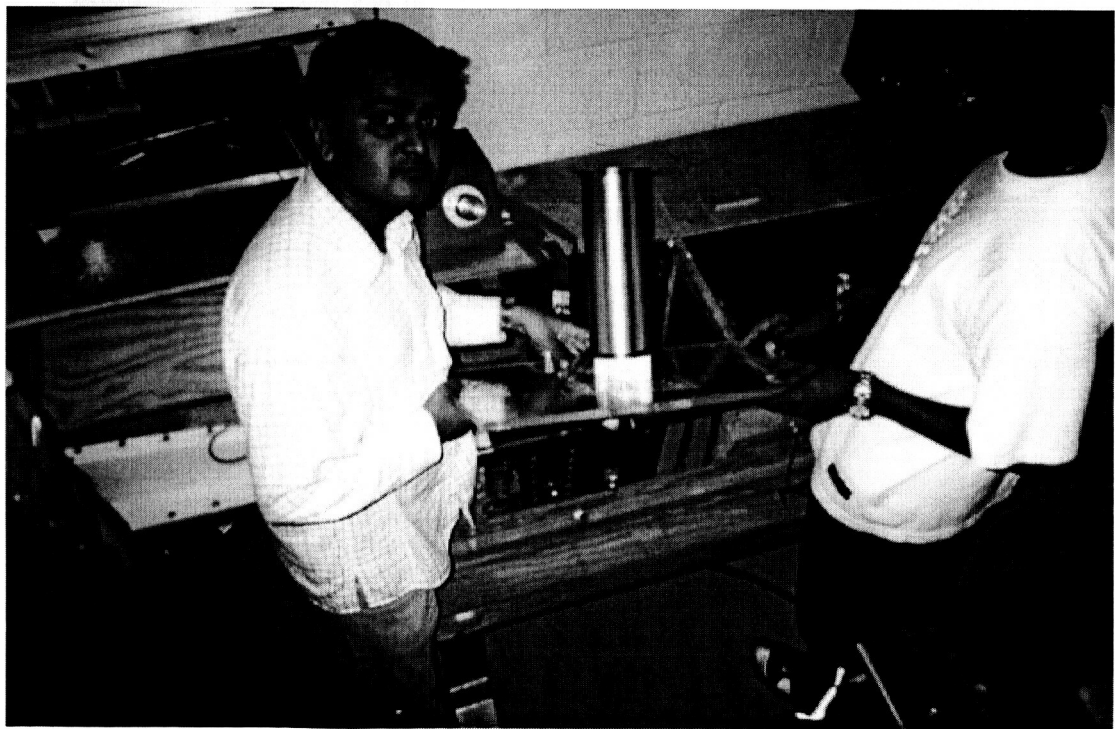


**Fig.6 Cold air jet injection from the Triangular-Round nozzle to the rectangular duct flow with cross flow Mach number,  $M_{\infty}=2$ . NSE based numerical simulation; NASA CFL3D code. Figures 7-9. In conclusion, several illustrations will be presented what show Hampton University students research and training activities.**

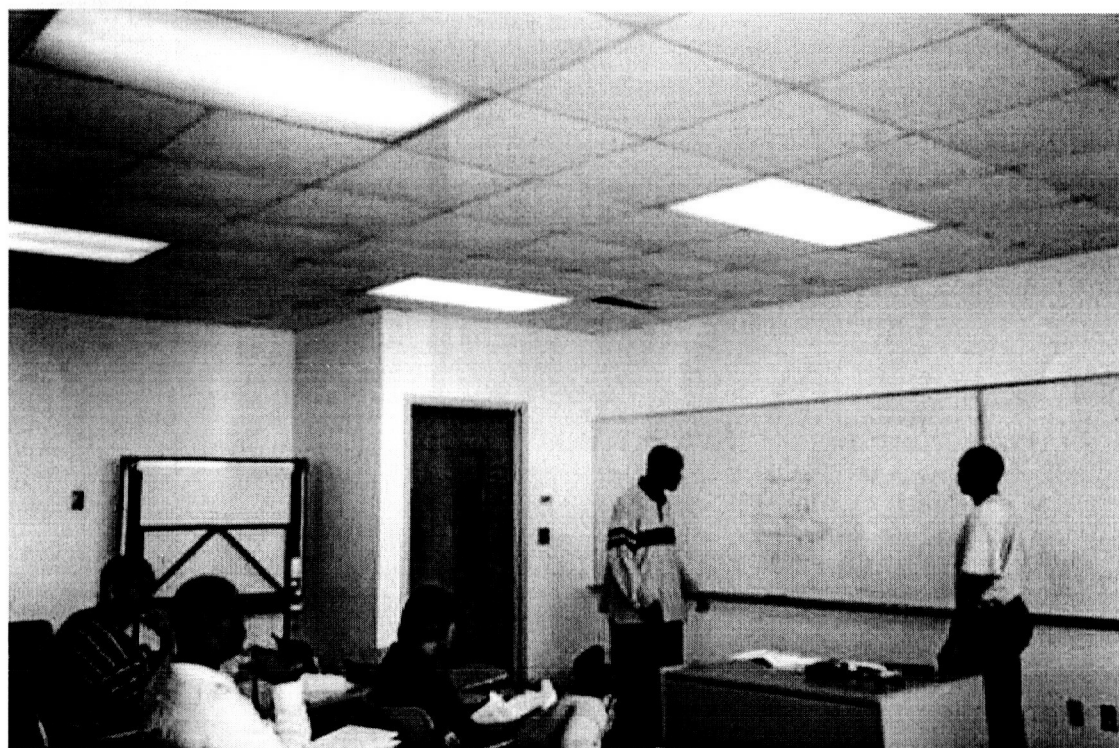
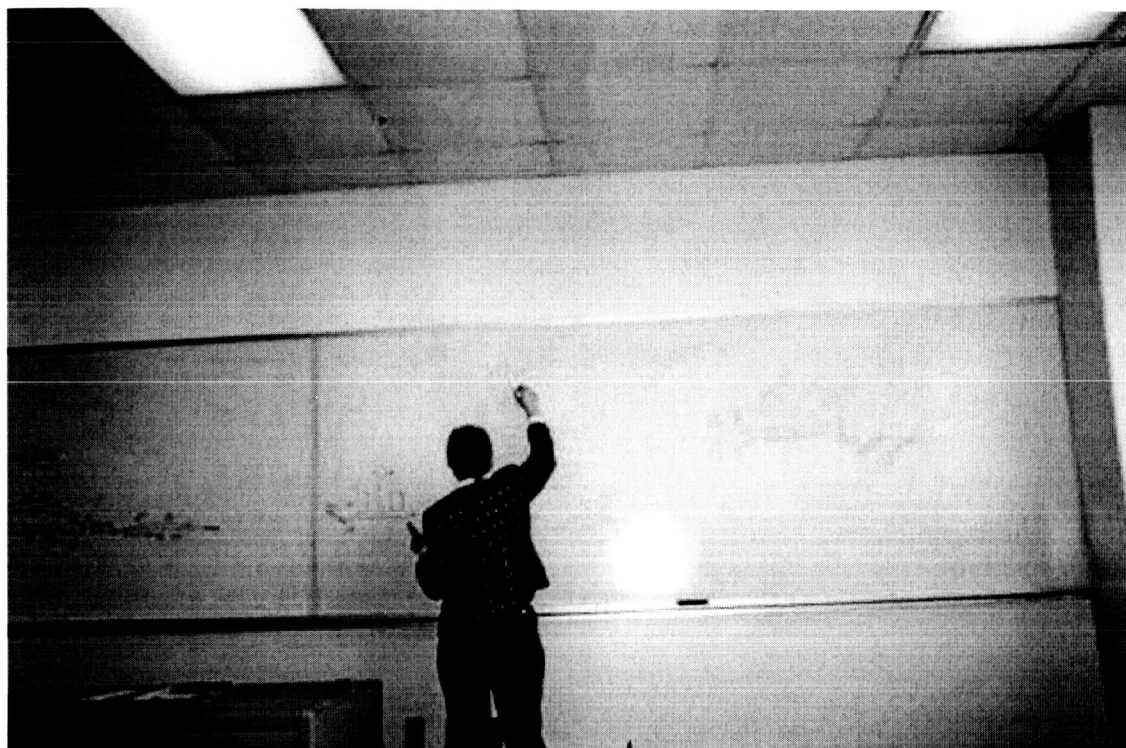


**Fig.7 Hampton University Low Speed Wind Tunnel (LSWT) at the Fluid Mechanics and Acoustics Laboratory (FM&AL). Experimental hall.**





**Fig.8 Hampton University Low Speed Wind Tunnel (LSWT) at the Fluid Mechanics and Acoustics Laboratory (FM&AL). Experimental hall. Research Professor, Dr. Mikhail Gilinsky, Graduate Research Assistant, Kaushal Patel, and Undergraduate Research Assistants, Casey Alexander, discuss the experimental setup.**



**Fig.9 Hampton University students attend the new course: “Advanced Aerodynamics and Aircraft Performance” lectured in the spring semester by the FM&AL researchers, Dr. M. Gilinsky and N. Sckholnikov (upper photo) with training in experimental tests using LSWT. Presentation of the joint project by two students before final exams (lower photo).**